DOCUMENT RESUME

ED 130 846 SE 021 406

AUTHOR Eaton, William W.
TITLE Geothermal Energy.
INSTITUTION Energy Research and Development Administration, Washington, D.C.
PUB DATE 75
NOTE 48p.; Photographs may not reproduce well

EDRS PRICE MF-$0.83 HC-$2.06 Plus Postage.
DESCRIPTORS *Earth Science; *Energy; Environment; *General Science; *Instructional Materials; *Natural Sciences; Physical Sciences
IDENTIFIERS *Geothermal Energy

ABSTRACT

Described are the origin and nature of geothermal energy. Included is the history of its development as an energy source, technological considerations affecting its development as an energy source, its environmental effects, economic considerations, and future prospects of development in this field. Basic system diagrams of the operation of a geothermal power plant are included. (SL)

****
* Documents acquired by ERIC include many informal unpublished *
* materials not available from other sources. ERIC makes every effort *
* to obtain the best copy available. Nevertheless, items of marginal *
* reproducibility are often encountered and this affects the quality *
* of the microfiche and hardcopy reproductions ERIC makes available *
* via the ERIC Document Reproduction Service (EDRS). EDRS is not *
* responsible for the quality of the original document. Reproductions *
* supplied by EDRS are the best that can be made from the original. *
****

Geothermal Energy

by William W. Ealou

ED130846

U S DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
EDUCATIGA

THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

SE 021 400

The U. S. Energy Research and Development Administration publishes a series of booklets for the general public.

Please write to the following address for a title list or for information on a specific subject:

USERDA – Technical Information Center
P. O. Box 62
Oak Ridge, Tennessee 37830

Dr. William W. Eaton, an independent consultant, holds a Ph.D. in physics from Yale University and is a registered Professional Engineer. He has extensive experience in industrial research and development, both in this country and abroad, and has been a Director or Trustee of numerous science-oriented organizations. He was closely involved with early applications of high-speed computers to problems of government and business.

For 3 years he served as Deputy Assistant Secretary for Science and Technology in the U. S. Department of Commerce. He has also been prominent in science affairs in Maryland. He headed formal studies on the environmental effects of nuclear power plants, both for the Governor of Maryland and for the Southern Governors' Conference

Dr. Eaton has prepared patents and articles in a number of technical fields, including several realated to various aspects of energy.

Chapter 1	INTRODUCTION	ii
Chapter 2	ORIGIN AND NATURE	3
Chapter 3	HISTORY	9
	Direct Use of Heated Water	9
	Generating Electricity	13
Chapter 4	GEOTHERMAL TECHNOLOGY	16
	Prospecting For Heat	17
	Drilling Technology	19
	Thermodynamics–Heat and Work	19
	Dry-Steam Wells	22
	Wet-Steam Wells	23
	The Secondary-Fluid Cycle	25
	Dry Hot Rock	25
	Other New Techniques	27
Chapter 5	ENVIRONMENTAL EFFECTS	30
Chapter 6	ECONOMIC CONSIDERATIONS	34
Chapter 7	FUTURE PROSPECTS	36
	Research and Development Programs	36
	Legal and Regulatory Aspects	37
	BIBLIOGRAPHY	39
	APPENDIX: Basic Units Related to Energy	40

U. S. Energy Research and Development Administration
Office of Public Affairs
Washington, D. C. 20545

Library of Congress Catalog Card Number: 75-600050
1975

Geothermal Energy

by William W. Eaton

CHAPTER 1 INTRODUCTION

Geothermal energy, which is the internal heat of the earth, is one of the most immense energy resources available to man. However, it has not been studied extensively, primarily because it exists at such great depths in most areas that it has been difficult to reach. But there is general agreement that vast and virtually inexhaustible quantities of heat would be available if one could drill far enough down into the earth at any location.

In contrast, coal, oil, and gas, which are the fossil fuels on which Americans have relied so heavily to provide the energy for their complex society, have recently become more costly and scarce. In addition, their increasing use has produced undesirable environmental effects that have proved difficult and expensive to control.

Although the U.S. has plenty of coal, there has been a growing and uncomfortable public realization that the continued dependence on the importation of large amounts of oil and gas is undesirable for economic and national security reasons.

Consequently, there has been a significant shift in the Nation's energy policy. This includes a renewed emphasis on finding, developing, and using other energy sources, which

are available domestically on a long-term basis, in order to help reach a condition of national energy self-sufficiency as soon as possible. These sources include nuclear fusion, solar energy, and geothermal energy. The Federal Government's research and development program in this broad field is the basic responsibility of the U.S. Energy Research and Development Administration (ERDA).

Although geothermal energy is already contributing to U.S. energy supplies in a small way at various locations, its development must be greatly accelerated if it is to assist in any significant fashion in meeting urgent and mounting energy needs.

This booklet contains a very brief outline of the general subject of geothermal energy, including information about its origin, nature, use, and the technological developments that must take place in order to increase its usefulness to mankind.

(In this book, metric units are given first followed by American units in parentheses. For example, 1000 square kilometers (400 square miles). Please note that all the units have in general been rounded off to the same number of significant figures. See Appendix on page 40 for a listing of basic units related to energy.)

CHAPTER 2 ORIGIN AND NATURE

The heat energy of the earth's core is evident most dramatically in volcanic eruptions. The sight of hot molten rock pouring from the earth, and the sensation, even at great distances, of its intense heat, brings a frightening realization of the fantastic quantity of energy involved.

Direct tapping and use of the heat of this molten rock, which geologists call "magma", is a fascinating possibility, but one that will require many years of study and development to bring to fruition. However, even if only a small portion of the total internal heat of the earth could be harnessed for useful purposes, there would probably be enough for centuries.

Geothermal energy is also abundantly evident in many other forms, some of which are quite spectacular, though less terrifying than a volcano. Geysers, such as "Old Faithful", result from the interaction of hot pressurized geothermal waters and underground cavities. Holes that emit vapor (fumaroles), hot springs, and bubbling mudholes are other examples of the internal heat of the earth breaking through to the surface.

Although in many areas of the world there is no perceptible evidence of geothermal heat at the surface, there is still a measurable underground flow of heat that is quite variable and depends upon geologic conditions. For example, temperatures in mines and wells usually rise with increased depth at an average rate of roughly 35° C per kilometer (100° F per mile) of depth. At the base of what geologists call the "continental crust",* the range of temperatures is 200°–1000° C (400°–1800° F). At the molten center of the earth, temperatures are believed to be in the range of 3500°–4500° C (6000°–8000° F). This internal heat is

*The continental crust is the outer 50–80 kilometers (30–50 miles) of the earth beneath the continents.

Figure 1 *The natural steam geyser called "Old Faithful" in Yellowstone National Park.*

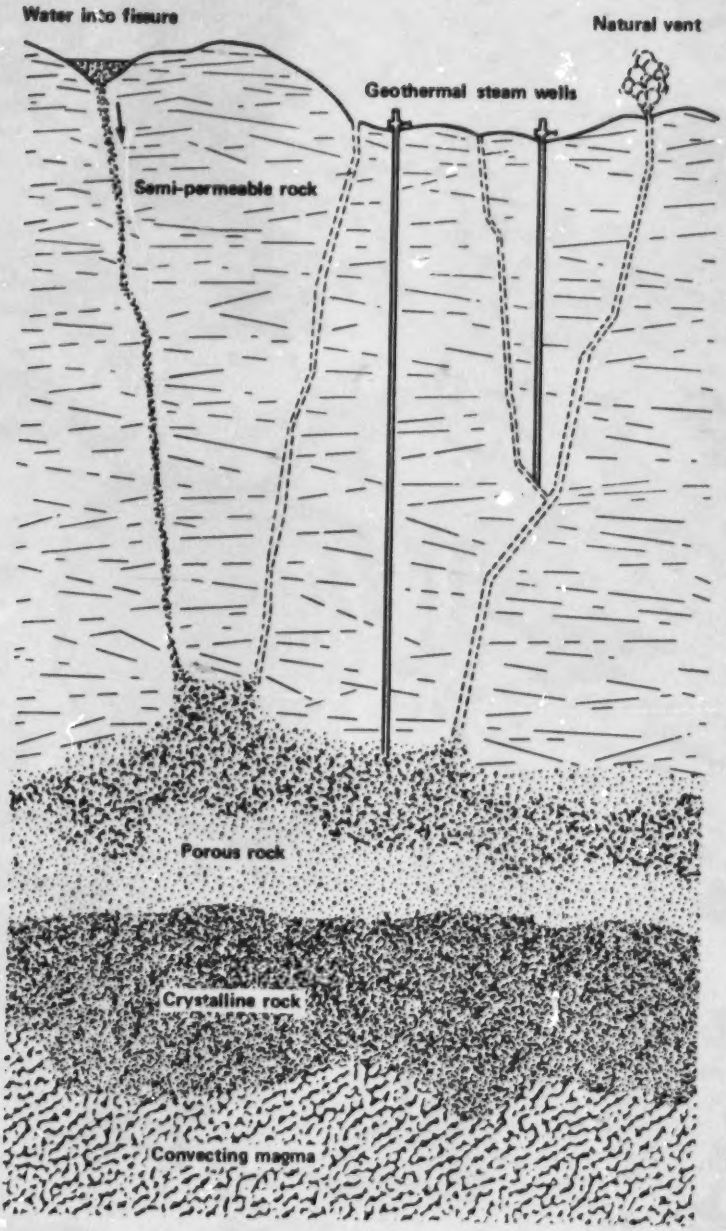
considered to be mainly the result of the natural decay of long-lived radioactive materials and thus virtually inexhaustible.

While these temperatures in the earth's crust represent average conditions, there are also significant concentrations of heat at much shallower depths—less than 3 kilometers (2 miles)—in certain locations. The energy stored in these "hot spots" can exist in solid rock, or in water and steam that fill cracks and pores in the rocks. The water and steam are sometimes at relatively high pressures, which may go above 135 atmospheres (2000 pounds per square inch) and at temperatures up to 300° C (570° F).

The geothermal energy in such a relatively shallow region is often observed as a natural hot spring or geyser and can be tapped by drilling wells at proper points. Since water under high pressure may exist as a liquid, even at temperatures far above its normal boiling point at the earth's surface, many such underground geothermal concentrations consist of liquid water rather than steam.

When the hot water in such a reservoir comes to the surface through a well, the high pressure is normally reduced and some of the water spontaneously boils, or "flashes", into steam. In this way a typical geothermal well yields a mixture of hot water and steam; the proportions depend on the temperatures and pressures at the particular location. These areas are called "wet-steam" fields. Some of the major fields of this kind are in Mexico, the Salton Sea–Imperial Valley area of California, and the Yellowstone region of Wyoming. Others are in New Zealand, Japan, the Philippines, Indonesia, Taiwan, and Turkey.

Figure 2 *Magma creates heat at a geothermal site. By convection the heat moves from the magma through crystalline rock to a layer of porous rock which contains water that has percolated down from the ground. Over the porous rock is relatively impermeable rock that contains the heat. Because it is deep in the ground the water is under high pressure and is therefore liquid. It expands and rises in a natural vent. As the pressure drops, the water begins to boil and produce steam. A well can tap the vent or the porous layer.*


Water into fissure
Natural vent
Geothermal steam wells
Semi-permeable rock
Porous rock
Crystalline rock
Convecting magma

The Salton Sea–Imperial Valley region is a good example of a potentially enormous source of geothermal energy in a wet-steam field that, if developed, could provide very important economic benefits for that section of the country. This active geothermal area covers approximately 1000 square kilometers (400 square miles), and temperatures of 300° C (570° F) have been verified at depths of only 1500 meters (5000 feet).

If this energy is to be usefully exploited, there are some serious technical problems as well as environmental, economic, and legal difficulties to overcome, which are covered in later chapters of this booklet. But if large quantities of very hot salty water could be brought to the surface, they could be partially "flashed" into steam at pressures that could be used to generate electricity. The steam would then be condensed into fresh water for many valuable uses in this arid territory. The remaining heavily mineralized water could either be returned to the ground or, under certain conditions, undergo further distillation to produce useful minerals. The development of the geothermal resources in this region could thus have a threefold benefit by yielding electricity, fresh water, and chemicals.

A relatively small number of geothermal heat concentrations produce superheated steam with practically no water. The steam from these "vapor-dominated" or "dry-steam" fields, if tapped, can be conveniently piped directly to steam turbines to generate electricity as described in Chapter 3. Only a very few of these fields are known to exist in the world at the present time. The main ones are located at Larderello in Italy and in The Geysers region in California.

In the U.S., many active geothermal areas are located near hot springs in the western states. Huge concentrations of hot water in large geologic basins are also known to lie under the Gulf Coast area of the U.S. at considerable depths. Many wells in this region have encountered large quantities of hot water under abnormally high pressures, but generally at relatively lower temperatures than those found in the wet-steam fields in the western states.

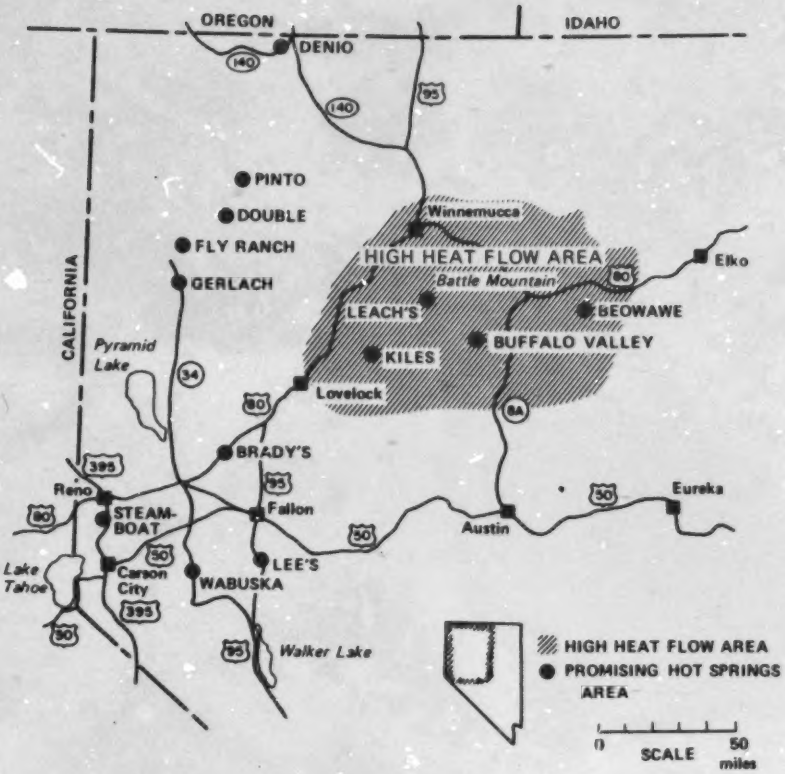


Figure 3 *Hot springs area in northwestern Nevada. The shaded area is a zone of high heat flow from underground rock formations. ERDA's Lawrence Berkeley Laboratory in California is studying the feasibility of using the heat from this water to generate electricity.*

Many of the hot rock masses underlying the U.S. do not come into contact with water systems at all and are therefore dry. It is generally considered that the total heat contained in these dry deposits is much greater than that which exists in wet-steam or dry-steam reservoirs. The problem of how to tap these tremendous dry heat resources, which have never been used, is discussed in Chapter 4.

There is not enough information now available to estimate accurately just how much total geothermal heat of all kinds is available in the U.S. From the information at hand, this has been calculated, down to a depth of 6 miles, to be the equivalent of burning one quadrillion (1,000,000,000,000,000) tons of coal. If made available at the surface, most of this energy could be used at least for direct heating purposes and would heat all the homes in the U.S. for thousands of centuries. It is not yet known exactly how much of it exists at high enough temperatures to be of practical use in generating electricity (for the reasons mentioned in Chapter 4 under the heading "Thermodynamics").

In Chapter 3 there are details of how the geothermal resources of the world—and particularly those in the U.S.—have been used in the past for various purposes.

CHAPTER 3 HISTORY

Hot springs, where underground geothermal water flows naturally to the surface, have been known and used since ancient times. Such watering places were developed by the Romans for recreational and medical purposes all around the Mediterranean and throughout their empire. Medical spas were also in existence in ancient Japan and elsewhere in the Far East. Hot springs are still popular as resorts in the U.S. and even more so at other locations throughout the world.

Most geothermal waters contain a variety of dissolved minerals, which are often considered to have medicinal value, and in some cases they might even be recovered economically. As an interesting illustration, the first recorded use of geothermal wells for commercial purposes occurred in 1812 in Italy and was not for heating but for the production of boric acid.

As pointed out in Chapter 2, some geothermal springs or wells yield steam in addition to hot water, and a very few produce dry steam alone. Useful applications for these various types have depended on the composition, the temperatures and pressures involved, and the geographical locations. It is convenient to discuss these applications under two general headings.

Direct Use of Heated Water

Iceland pioneered in the 1930s in using geothermal hot water for household and commercial heating purposes. An elaborate network of pipes and conduits carries hot water from more than 100 geothermal wells in the vicinity of Iceland's capital, Reykjavik, to 90% of its homes. The deepest well is about 2000 meters (7000 feet) and the temperatures of the basic geothermal reservoirs range from just under the boiling point to 150° C (300° F). The hot water is carried for distances up to 16 kilometers (10 miles) and is delivered at about 80° C (175° F).

Figure 4 *A steam borehole in Iceland. Most of the homes in Reykjavik, the capital city, are heated by using geothermal wells.*

An additional 25,000 people in towns and villages outside the Reykjavik area will also soon receive geothermal water for a variety of direct heating applications. In addition to house heating, the water is widely used in Iceland for heating baths, swimming pools, and greenhouses, which furnish fresh vegetables throughout the year.

In the U.S., geothermal space heating has been successfully carried out for many years in southern Oregon. At Klamath Falls, for example, geothermal water from 350 wells supplies heat, either directly or through heat-exchanger systems, to pure municipal water, which is used for heating buildings.

In other parts of Oregon, geothermal waters are used for greenhouses, baths, farm buildings, schools, and resorts. Similar projects have been undertaken in Boise, Idaho, in towns in California, and in some farms and villages in other western states.

In Japan there has been extensive exploration for geothermal resources, which have been employed for a variety of direct heating applications over the last half century. The first geothermal heating of greenhouses began in the early 1920s, and this technique is still widely used today to produce many kinds of vegetables and tropical fruits. Although space heating there has not been developed as widely as in Iceland and the U.S.S.R., Japan has thousands of natural hot mineral water resorts, baths, and therapeutic spas, and probably leads the rest of the world in the use of geothermal resources for these purposes.

There are also several different kinds of industrial applications in Japan, including sulfur recovery, commercial baking, salt recovery from seawater, and experimental fish farming.

In the U.S.S.R., there has been considerable development of geothermal heating systems over a wide geographical area. At several locations, centralized municipal geothermal heating installations furnish hot water and heat houses for communities of 15,000–18,000 people. Geothermal energy is also used in the Soviet Union in an oil refinery and as a heat source for greenhouses, seedbeds, and baths. Although precise information about the total consumption of geo-

thermal energy in direct heating applications in the U.S.S.R. is not known, it is believed to be the equivalent of over 1,000,000 tons of fuel oil per year.

In Hungary, geothermal reservoirs have been found under large areas and have been widely used for space heating applications. For exampie, some 1200 housing units and associated municipal and commercial buildings are heated by hot geothermal water in the city of Szeged at costs well below those of conventional fuels. Geothermal heat is also used extensively in Hungary for agricultural purposes, such as heating greenhouses and farm buildings and drying crops. Such applications are expected to increase during the next decade.

New Zealand is another country in which extensive use has been made of direct geothermal heating for several different applications. At one place, natural steam from a number of wells is used to heat pure water for the generation of high quality steam, which is used directly in a number of industrial mill processes. This steam is also used to operate log-handling equipment, dry timber, and generate electricity.

In the New Zealand city of Rotorua, which has a population of 30,000, there are more than a thousand hot water wells that supply heat to commercial establishments, houses, schools, hospitals, and hotels. There is also a hotel in the city with a geothermal air-conditioning system, which has a very low operating cost. Additional direct heating applications for geothermal energy in New Zealand are in agriculture.

There are many other countries where direct geothermal heat has been used successfully and economically. Such applications are limited, however, to the immediate geographical region of the wells.

From the standpoint of distribution, a much more flexible way of using geothermal sources is through the generation of electricity, which is discussed below. But up until the present time, this has been practical with only a relatively few geothermal deposits.

Figure 5 *A view of a geothermal steam field in New Zealand that is used to produce electricity.*

Generating Electricity

Generation of electricity from naturally occurring steam was first undertaken in Italy at Larderello in 1904. As early as 1913, a 250-kilowatt station was established, and electricity has been generated geothermally at this location almost continuously ever since. The present level is about 365 megawatts (365,000 kilowatts). There are thirteen individual plants included in the Larderello geothermal area, which is now being used nearly to capacity.

Geothermal electricity generating stations of various sizes have also been established in various other foreign countries including New Zealand, Japan, Iceland, the U.S.S.R., and Mexico. The largest such installation, and the only one in the U.S., is located in the state of California at a geothermal steam field known as The Geysers.

The development of electric power generation has proceeded rapidly at The Geysers, which is the only operating field other than Larderello that has dry steam rather than hot

water. The first 12-megawatt turbine was installed in 1960, and since that time additional plants have brought the present capacity to over 400 megawatts. Based on a steady expansion of this field, the final total capacity now planned is almost 1200 megawatts, which will make it by far the largest complex of its kind in the world and sufficient to meet the power needs of a large metropolitan area.

Figure 6 *Venting geothermal wells and gathering pipes at the Geysers, a geothermal steam field in California.*

There are various estimates of the total sustainable geothermal power available at The Geysers field. These are based on different interpretations of data concerning the extent of the field, the yield and spacing of the wells, and the total fluid stored in the reservoirs. These estimates range up to 4000 megawatts.

In The Geysers area, which is about 3 by 13 kilometers (2 by 8 miles), over 100 wells have been drilled; the deepest of these is more than 2300 meters (8000 feet). Temperatures of the reservoirs from which the heat is drawn are about 255° C (480° F). The basic source appears to be a mass of heated rocks at a depth of 5–8 kilometers (3–5 miles) and covering an area of about 250–1300 square kilometers (100–500 square miles).

CHAPTER 4 GEOTHERMAL TECHNOLOGY

Geothermal technology covers a wide range of different scientific and engineering fields. The most important of these fields are outlined briefly in this chapter.

First there are the problems of identifying and evaluating new geothermal resources. This process uses geophysical exploration instruments and techniques that are similar to those used in prospecting for petroleum or minerals.

The next problem is to reach these heat concentrations and devise satisfactory methods for bringing the heat to the earth's surface. This involves the technology of drilling geothermal wells. Facilities must then be designed and built to utilize the heat in a practical and economical manner without adverse environmental effects.

In connection with the use of heat, especially in the generation of electricity, it is important to understand the limitations imposed by some of the basic principles of thermodynamics, which is the science that deals with the relationship between heat and work. Accordingly, a brief outline of this subject is included in this chapter.

For the purpose of discussing how geothermal heat can best be used, it is convenient to divide geothermal resources into three major classes as indicated in Chapter 2:

1. Those that produce steam alone—the dry-steam field.
2. Those that yield mixtures of steam and hot water in widely varying proportions depending on different temperatures and pressures caused by geologic factors.
3. Those that consist of hot rock which has not come into contact with water and is hence in a dry condition.

Experience indicates that the geothermal sources which produce only steam are relatively rare. This is unfortunate because the technology to use dry steam has been reasonably well developed.

On the basis of present knowledge, it seems that the wet-steam areas are perhaps twenty times more plentiful than the dry-steam fields. The technology for using wet-steam fields varies widely in accordance with a number of factors,

such as the proportions of steam and water, the temperatures, the impurities, the pressure, and the depth of the wells.

The technology of identifying and exploiting dry hot rock is in a very early stage at the present time. However, the total amount of heat available in such deposits is frequently estimated to be at least ten times the total heat contained in the wet- and dry-steam fields combined.

Finally, there have been some basically new and imaginative concepts recently proposed to improve the efficiency and economics of geothermal heat utilization. These are discussed briefly at the end of this chapter.

Prospecting For Heat

Geothermal heat sources must be accurately located and analyzed before they can be used. Hence it is very important that more reliable and economical geothermal prospecting techniques be developed. This is a challenge to scientists and engineers to apply all possible related knowledge to this subject. Prospecting for geothermal heat sources has much in common with prospecting for petroleum deposits. Many of the highly scientific and sophisticated prospecting techniques developed by the petroleum industry have important applications in locating and identifying geothermal resources.

In the past, geothermal exploration, using petroleum prospecting methods, has been generally confined to locations in the vicinity of hot springs. Such techniques have not been widely employed to discover and evaluate possible new geothermal fields prior to drilling, nor have new specialized methods been well developed.

One of the most important first steps is to outline broad regions where the outward flow of heat near the earth's surface is significantly greater than average. However, temperature measurements right at the surface can for various reasons be misleading, and it is therefore more reliable to measure how fast the temperature is increasing with depth at distances of 30–90 meters (100–300 feet) underground.

Figure 7 *Geothermal Engineers from ERDA's Lawrence Berkeley Laboratory pour water, salt, and detergent around an aluminum electrode in a Nevada desert trench as part of a system to detect underground hot water reservoirs by measuring the earth's electric resistivity.*

Aerial surveys, including those using infrared rays, can be useful but may also be affected by factors other than geothermal heat deposits. Many other heat prospecting approaches are now being investigated more thoroughly. Some of these are: measurement of the electrical conductivity (which is related to temperature) of rock masses at

various depths; magnetic, electromagnetic, and gravity measurements; and seismic methods. Chemical analysis of geothermal waters can also give information about the nature of heat concentrations.

Sometimes an explosive charge is dropped down a test well. The sound waves created by the explosion travel in various ways depending on the types of rocks and soil in the vicinity. Measurements of these waves help geologists determine the location of geologic structures that may contain petroleum, mineral deposits, or geothermal reservoirs.

Drilling Technology

At the present time, well-drilling techniques in the U.S. are adequate up to depths of about 6000 meters (20,000 feet) and temperatures around 200° C (400° F). Costs increase sharply beyond these limits, and the accuracy of information about conditions at the bottom of the well—"well-logging"—deteriorates rapidly. If it is true, as many geothermal experts agree, that vast heat concentrations lie at considerable depths under most of the U.S., then it is important that the technology of deep drilling at high temperatures be improved. Perhaps only in this way can geothermal resources eventually be made available economically to the whole nation.

In addition to improvements in well-logging instruments, it will be necessary to develop better high-temperature drilling fluids and new drilling techniques, such as electric melting penetrators and turbine drills.

Based on all available evidence, a deep-drilling research program will be essential to the accurate evaluation and utilization of new geothermal resources.

Thermodynamics—Heat and Work

Energy—the capacity to do useful work—can exist in several different forms. Heat is one form, first discovered by early man as fire and still the most important source for

many applications. Another form is kinetic energy—the energy of mechanical motion—as illustrated by a moving vehicle, a pile driver, or a steam turbine.

In the early days of history, wood was the chief substance burned to produce heat. But within the last two centuries, the largest amounts of heat energy produced by civilized man have come from burning the fossil fuels—coal, oil, and gas.

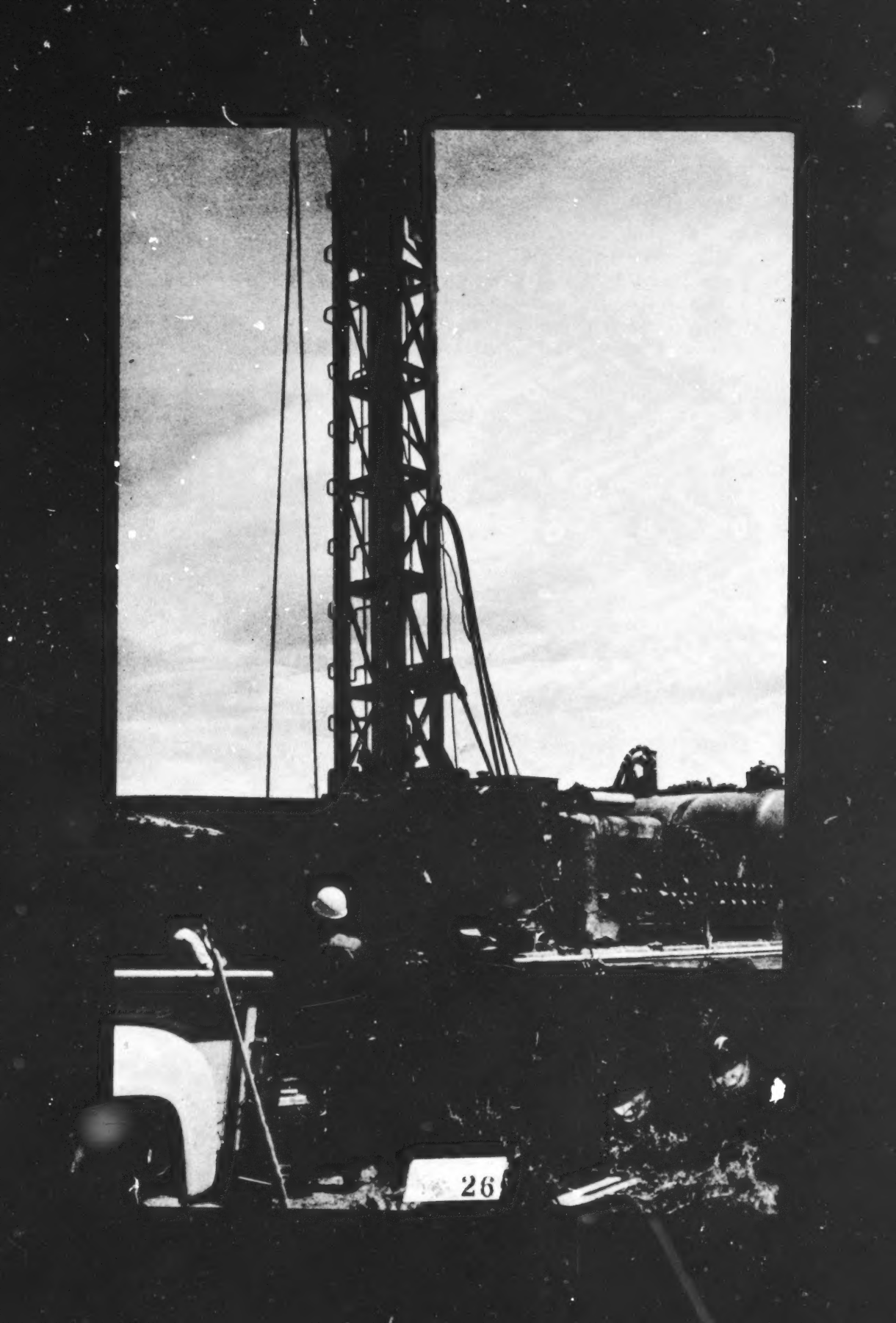
Heat energy has always been used directly for household and industrial purposes, and these direct applications still amount to 30% of all the energy consumed in the U.S. Since the discovery of the steam engine and later the gasoline engine, large amounts of heat have also been used to power machines and provide means of transportation.

Around the turn of the 20th century, heat energy began to be used extensively to generate electricity, which is still another form of energy that has unique advantages for distribution and convenient use. In the last half century, the demand for electricity has almost doubled each decade. More than 98% of all U.S. farms have electricity, and our country now consumes about 33% of all the electric power generated in the world although it has only 6% of its population.

As the name suggests, thermodynamics is the science that involves the interaction between heat and work. One fundamental principle is that a heat source cannot be used to produce mechanical work unless the heat can flow to a region of lower temperature, i.e., a "heat sink." Furthermore, the amount of useful work that can be obtained in any kind of heat-using machine or engine depends largely on the temperature of the heat source relative to that of the heat sink.

A heat source can be compared in some ways—although not exactly—to a body of water that is confined at a specific level, such as a lake or reservoir. No matter how much water is available, it will not produce useful work unless it can flow to a lower level. Furthermore, the higher the initial level, the more work produced as the water flows to the lower level. As

Figure 8 *ERDA's Idaho Operations Office is using this test hole drilling rig to determine the feasibility of harnessing geothermal water for electric power generation and for heating and agricultural purposes.*


26

in this water analogy, the amount of mechanical work that can be extracted from a source of heat, no matter how large it may be, is limited by the difference between the temperature of the heat source and that of the region to which it flows. This is true for all kinds of engines, turbines, or other machines that convert heat into work.

In an automobile engine, for example, only 10%–20% of the energy of the burning gasoline is transformed into work. None of the original energy actually disappears, but the large fraction that is not converted to work is discharged to the environment as waste heat in the radiator and exhaust.

On the other hand, if heat energy is used to produce high-temperature steam, 30%–40% can be converted to work by turbines in order to generate electriciy as in steam-electric power plants. In these cases, the remaining energy also goes to the environment—usually into large bodies of water or through cooling towers to the atmosphere.

Most geothermal sources provide heat energy that is contained in hot water and/or steam at temperatures of 150°–250° C (300°–480° F), which are much lower than those used in modern steam-electric plants. The overall efficiencies of power plants using such geothermal energy are hence correspondingly less than those of fossil or nuclear plants for the reasons given above. In those instances where geothermal waters provide heat at a temperature in the lower portion of the above range, ordinary steam turbines do not operate properly, and new technologies must be developed, such as the vapor-turbine cycle discussed later in this chapter.

Dry-Steam Wells

The technology of using dry steam from geothermal wells, which is done at The Geysers in the U.S. and at Larderello in Italy, is well developed and is analogous to that of modern steam-electric plants except for a different range of pressure and temperature.

By the time the steam from typical natural steam wells reaches the turbines, it is at a pressure of 7 atmospheres (100 pounds per square inch) and about 200° C (400° F) in contrast to pressures of 200 atmospheres (3000 pounds per square inch) and temperatures over 540° C (1000° F) for modern power generating stations using fossil fuels. Because of these lower initial temperatures, the geothermal plants have a lower efficiency—about 14%—as compared with 40% for the latest fossil plants as explained above. But after the geothermal steam leaves the turbines, which must be of special design, it is processed in the same way as in fossil plants. First it is condensed and the water containing the waste heat is then fed to cooling towers or disposed of in other ways depending on the local conditions.

Wet-Steam Wells

Much more common than the rare dry-steam wells are those yielding a mixture of hot water and steam in different proportions depending on a number of factors, mainly pressure and temperature. The steam can often be separated and used to generate electricity; the remaining hot water can be employed for many different purposes. The technology of using geothermal water for various direct heating applications is relatively simple except for problems relating to the dissolved minerals that, in many installations, foul the piping and heat exchange equipment.

Installations have been established where some of the hot geothermal water, after separation from the steam, can be distilled by its own heat using low pressures. An extension of these ideas has been proposed that would have a threefold purpose. Steam from a wet-steam well would be separated and used to generate electricity. The hot water would be fed into a desalination plant, and a portion would be used to produce fresh water. The remaining water, with an increased concentration of minerals, would be evaporated to yield those minerals. The design is still being studied.

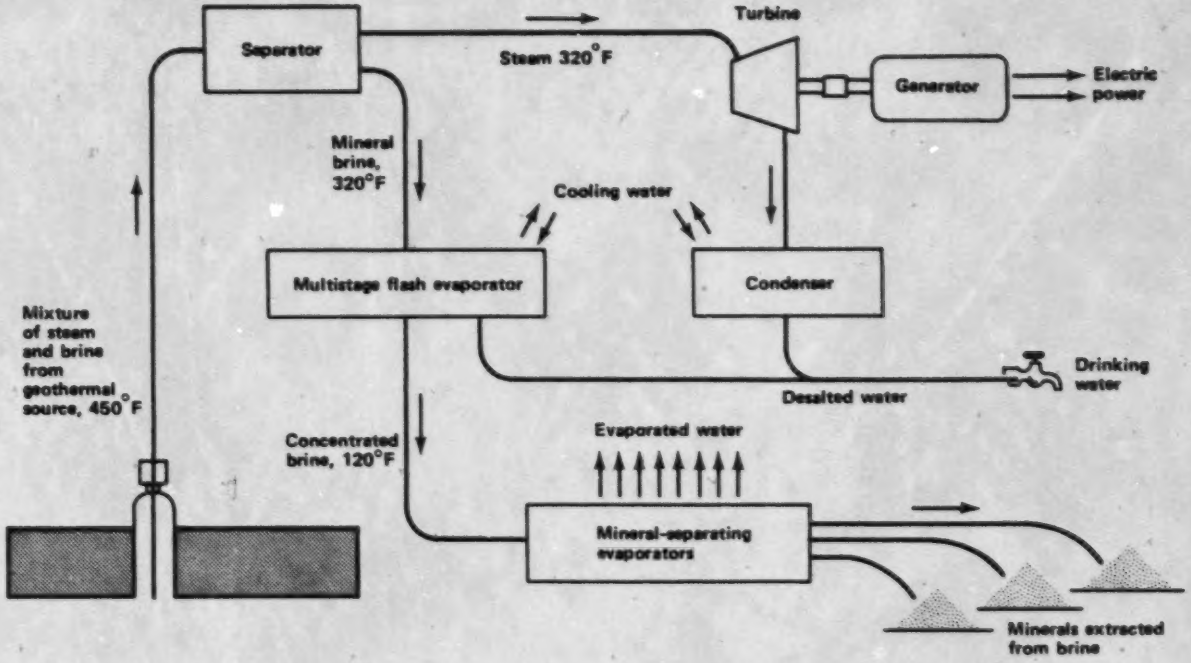


Figure 9 *In this multipurpose scheme, being developed for a geothermal field in Chile, the geothermal source produces a mixture of steam and mineral-rich brine. The steam and brine are separated, and the steam drives a turbine to produce electric power while the brine is put through an evaporator that concentrates it, thereby producing desalted water. The concentrated brine goes to a separator that extracts the minerals.*

The Secondary-Fluid Cycle

This is a relatively new process in which the hot water is brought up from a geothermal reservoir and kept at relatively high pressure throughout the process so that it does not boil and produce steam. Through a heat exchanger it gives up most of its heat and causes a secondary fluid, such as isobutane or freon, which has a lower boiling point, to vaporize. This vapor expands through a turbine to drive an electrical generator and is then condensed to a liquid before being returned to the heat exchanger to start the cycle all over again.

The original geothermal well water, still at high pressure but having lost most of its heat energy, is forced back into the ground. This procedure tends to maintain the underground pressure at a useful level and prevent subsidence (lowering) of the local ground level. At least some of the returned water may come into contact again with the basic geothermal heat source.

There are many advantages of the secondary-fluid concept. Among these are: smaller turbines, reduction of the heat losses that occur in an unpressurized well when some of the hot well water flashes into steam on the way to the surface, and reduced atmospheric pollution under certain conditions. A plant of this kind, now in operation in the U.S.S.R., uses freon as the secondary fluid. Similar plants are planned in Japan.

Dry Hot Rock

As mentioned previously, there is evidence to indicate that the total geothermal heat energy in dry hot rock is much greater than that associated with hot water and steam systems. However, there has not been any use of this resource to date, primarily because there is no technology concerning it.

The U.S. Energy Research and Development Administration's Los Alamos Scientific Laboratory in New Mexico is

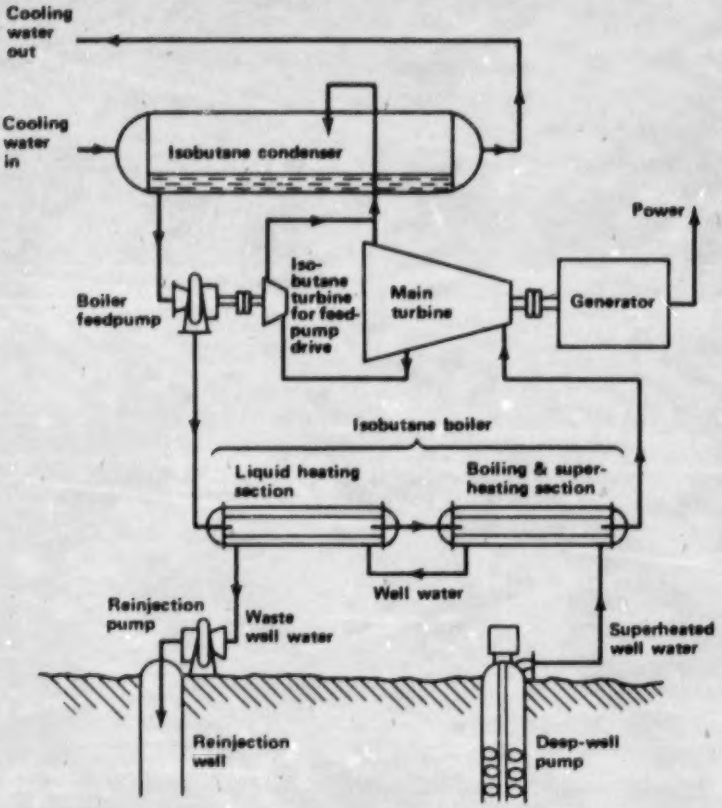


Figure 10 *Diagram of a vapor-turbine cycle for geothermal power generation.*

working on a new approach to this problem. The method, based on the hydrofracturing technique already extensively used in the petroleum industry, has not yet been clearly demonstrated as being practical for the kind of rock formations that contain geothermal heat deposits.

The first step is to pump water under very high pressure down into a dry hole to open a large vertical crack in hot rock, such as granite, which overlies an area of high heat

flow from the earth's interior. A second hole is drilled down to intersect the crack. Subsequently, cold water is forced down through the crack, becomes heated, and then returns to the surface to provide energy for power plants or other applications.

Recent experiments in New Mexico offer hope that some of the uncertainties regarding this proposed method can be resolved. These indicate that the granite can indeed be fractured successfully, and that the crack will retain the water tightly. It is believed, but has not yet been demonstrated, that the hot rock will tend to contract as it cools so that the initial crack will be extended to make new hot rock available for the extraction of additional heat.

Another method of using these sources of dry heat is to create large artificial cracks with explosives, and then to circulate water from the surface through the extended areas of the cracks in order to extract the heat. This technique requires further investigation because there are several major problems, such as the effect of blast waves on surface facilities, the economics of creating sufficient fresh rock surface to extract heat in useful quantities, and the limitation on how fast the rock will conduct heat to the cracks where it is being withdrawn.

Development of techniques to use dry hot rock has just begun, but the results so far are promising.

Other New Techniques

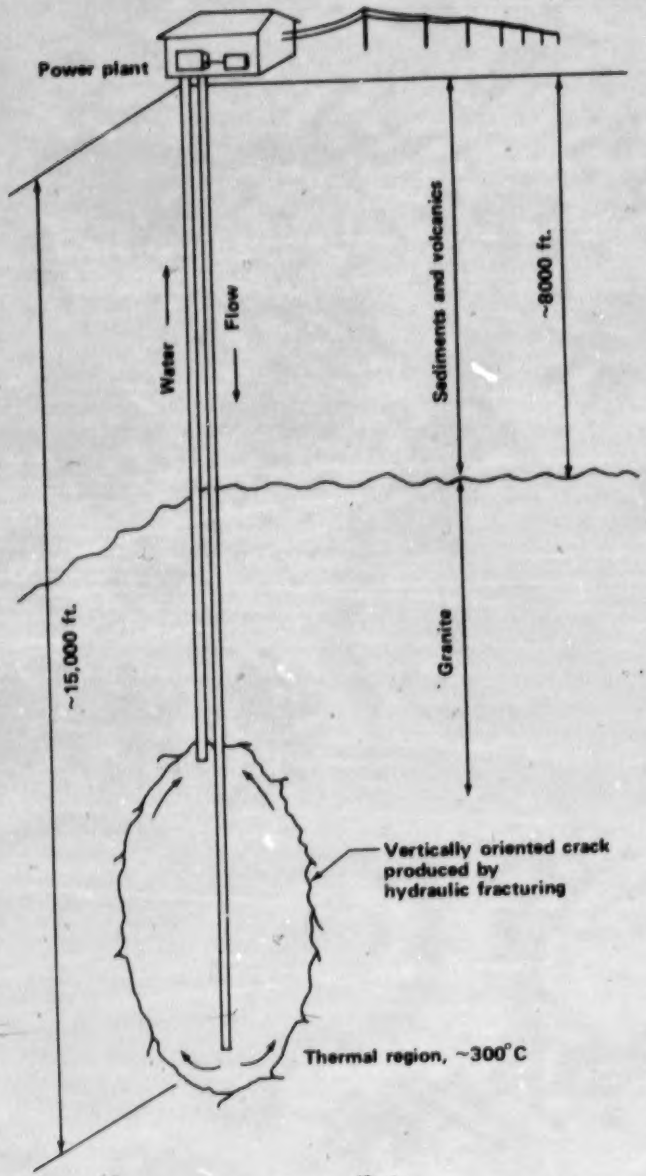
Other concepts have been proposed to advance the technology of geothermal energy use. One proposal of ERDA's Sandia Laboratories in New Mexico is to make a direct tap into molten rock or magma, possibly near a volcano, and install a collector or heat exchanger to bring the heat to a power plant on the surface. With temperatures of 1000° C (1800° F) or more, the heat would be available in almost limitless quantities. It is estimated that a cubic mile of such material contains enough heat to run several 1000-megawatt electric plants for a century. However, there are

many formidable technical problems to be solved, such as the selection of the proper materials for the heat exchanger, which must last for a reasonable period of time at the high temperatures involved, and the technology needed to bring about the required flow of the molten rock around the collector so as to maintain the necessary transmission of heat.

Another proposal, which does not appear to require such radical extensions of present technologies, has been formulated at ERDA's Lawrence Livermore Laboratory in California for application to the hot waters of the Salton Sea area in California, which contain heavy concentrations of minerals.

The basic idea is called the "total flow" concept. The object is to convert some of the thermal energy of a pressurized-steam, hot-water mixture into kinetic energy by forcing it through a converging-diverging nozzle. The resulting high-velocity jet output would be used to drive a modified hydraulic impulse turbine. Theoretically, this method should produce 60% more power than other systems, operational or proposed, for this type of application. The advantage is that the total flow is used, and this allows recovery of some energy in the liquid that would otherwise be lost. Much of the necessary technology already exists, and preliminary estimates indicate that the capital and operating costs will be attractive.

Figure 11 *ERDA's Los Alamos Scientific Laboratory in New Mexico is developing this system for extracting energy from a dry geothermal reservoir.*


Power plant
Water
Flow
Sediments and volcanics
~8000 ft.
~15,000 ft.
Granite
Vertically oriented crack produced by hydraulic fracturing
Thermal region, ~300°C

34

CHAPTER 5 ENVIRONMENTAL EFFECTS

Generally speaking, the practical use of geothermal energy has some special advantages from an environmental standpoint compared with other methods of energy production or generation. One very important basic advantage is that the environmental effects associated with geothermal power generation are generally restricted to the immediate vicinity of the plants. This characteristic is in marked contrast to coal, oil, and nuclear installations, all of which involve a wide variety of environmental impacts far removed from the generating plants themselves.

In the case of coal, for instance, the mining and transportation activities, as well as the final disposition of the ash and other combustion products, are usually at some distance from the plant. For oil-fired plants, distant activities include extracting and transporting the crude oil, the refining processes, the transmission of fuel to the plant, and the disposal of undesirable combustion products. In the case of nuclear plants, some of the different essential activities undertaken at widely separated locations include mining of the ore, a complex series of industrial processes, and the ultimate disposal of the potentially hazardous spent fuel.

Another environmental advantage of some geothermal installations is that the dissolved minerals in the waste water can be separated out, and this results in fresh water that can be important in arid regions. This condition is found, for example, in the Salton Sea–Imperial Valley region of Southern California, as mentioned in Chapter 2.

Despite these advantages, the use of geothermal energy resources does present special environmental considerations that must be carefully evaluated for each installation. The more important of these are:

- Prior to the construction of a geothermal facility, the noise and other objectionable aspects of well drilling may be important depending on the specific location. Noise may also continue to be a problem after operations begin.

Figure 12 *A pipeline channels brine from an existing geothermal well near the Salton Sea–Imperial Valley area of Southern California to ERDA's Lawrence Livermore Laboratory in a project that seeks to harness the flow of hot salt water for the generation of electricity.*

- It is necessary in certain instances to provide safe disposal methods for toxic and saline liquid wastes involved in some geothermal hot water fields. Reinjection of such fluids back into the geologic formation is a possible solution, but it has not been fully investigated.
- Geothermal fluids, both liquid and steam, often carry substantial amounts of dissolved gases that are released upon loss of fluid pressure or condensation of the steam. Commonly encountered gases are carbon dioxide, hydrogen sulfide, methane, and ammonia. Although carbon dioxide is relatively harmless when discharged into the atmosphere, hydrogen sulfide and methane can be dangerous and/or objectionable depending on concentration and must be properly controlled. Ammonia occurs only infrequently and, particularly in low concentrations, is not regarded as a hazard.

- Withdrawal of substantial volumes of fluids from geological formations over relatively long periods of time has caused extensive differential land subsidence in the Wairakei geothermal field in New Zealand and during petroleum extraction in the U.S. Land subsidence, which in the petroleum industry has been controlled by repressurization with water, is irreversible and can be damaging to irrigation, flood control, and sewer systems, as well as to structures such as railroad beds, airport runways, and foundations.
- It is even possible to trigger earthquakes by the high-pressure injection of fluids into geologic formations if they are in direct contact with seismically active faults. Present evidence indicates that such consequences can be avoided by eliminating the possibility of any hydraulic contact with a seismic fault.
- Subsurface groundwater contamination can be caused by improper well drilling and cementing procedures.
- Under atmospheric conditions, it is possible that local fogging may result from the release of large amounts of water vapor from a geothermal facility where flashing of the hot pressurized water occurs.
- For applications related to direct heating, such as for household, industrial, or agricultural purposes, the environmental impact is related mainly to the ultimate disposal of the water, which usually contains many dissolved minerals.
- In geothermal power plants using relatively low-temperature steam, there is more waste heat dissipated to the environment than from fossil or nuclear power plants of the same generating capacity that operate at much higher temperatures. This is because, as noted in Chapter 4, the overall efficiency of transforming heat into mechanical (and, in turn, electrical) energy is limited by the difference between the initial steam temperature and the final condenser temperature. For example, the electrical power output of the plants at The Geysers field in California averages about 14% of

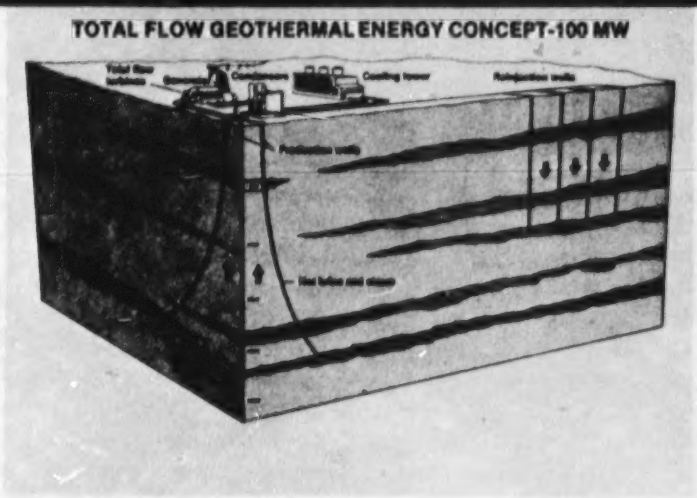


Figure 13 *Hot brine and steam are put through a turbine to produce electricity. The residue is reinjected into the ground thus eliminating the environmental problem of disposing of large amounts of salt.*

the total heat energy of the input steam. The remaining 86% must be dissipated to the environment in some acceptable way.

- For those geothermal electrical generation systems designed to start with hot water instead of steam—as in the secondary-fluid cycle described in Chapter 4—the overall efficiencies may be even less because of still lower initial temperatures. Hence, the fraction of the extracted geothermal heat passed on to the environment via the condenser cooling water may be over 90%. However, the heat still remaining in the original geothermal water will be returned to the ground as the water is re-injected; this procedure has the additional environmental advantage of preventing subsidence.

Despite the environmental considerations mentioned above, which may or may not be problems in any particular installation, the use of geothermal energy resources appears to have environmental advantages that generally outweigh the drawbacks. Additionally, the technology to deal with these environmental effects exists, although each such facility must be considered as a special case.

CHAPTER 6 ECONOMIC CONSIDERATIONS

The most basic economic fact about geothermal energy is that once tapped, the "fuel"—the natural heat of the earth—is free. However, overall production costs associated with various kinds of geothermal energy installations are generally difficult to compile for comparative purposes because the background data and assumptions are not always available. Different tax rates and amortization periods may be involved as well as a number of hidden costs and other variables.

In direct heating applications in various foreign countries, such as Hungary, Iceland, New Zealand, and the U.S.S.R., it seems to have been clearly shown that the use of geothermal heat in agriculture, industry, and household heating is definitely less expensive than the use of other fuels for the same purposes. In Iceland, for example, the direct use of hot geothermal water for heating buildings is cheaper than providing the heat by any other means, including hydroelectric power.

Natural gas and coal have in the past been competitive in cost with geothermal energy for direct heat applications. However, gas is becoming increasingly scarce and costly, and coal produces serious environmental effects that are expensive to control in order to meet today's pollution standards.

At present, there are so few geothermal electric power plants that it is difficult to draw meaningful conclusions regarding the economics of these plants compared with fossil, nuclear, and hydroelectric plants. However, the best available information indicates that the overall cost, including capital amortization, of geothermally produced electricity—such as at The Geysers in California—is less than that for fossil and nuclear plants, but higher than for hydroelectric installations.

One economic advantage of geothermal power installations at certain locations is that they are practical even in relatively small sizes that are not economically feasible for other kinds of power plants. As an illustration, in Iceland many small noncondensing geothermal turbines are economically operated to generate electricity for villages and farms.

Some of the basic costs associated with providing geothermal energy, such as drilling costs, are well-known. Other important cost elements, such as those related to the life expectancy of the "fuel", routine maintenance, and environmental control, are not known and are difficult to estimate now, but in geothermal desalination plants, they are estimated to be well below those of other methods.

With the development of multipurpose geothermal plants for several combined end products, such as electricity, hot water uses, desalination, and mineral production, the economic benefits can be expected to be correspondingly greater than for single purpose facilities. Today it is estimated that an electric plant using natural geothermal steam can be built for an expenditure far below the capital costs for a modern fossil or nuclear plant of the same capacity. On the other hand, a series of proposed demonstration geothermal power plants that will be constructed to test some of the new complex designs, such as the secondary-fluid cycle mentioned in Chapter 4, will probably cost initially at least as much as fossil or nuclear installations of comparable size. Eventual capital investment costs for such facilities cannot be forecast at this time.

CHAPTER 7 FUTURE PROSPECTS

Geothermal energy could, if more extensively developed, play a significant part in the future increase of this country's total energy resources to meet rapidly mounting demands. But quantitative forecasts by knowledgeable experts differ widely, mainly because of insufficient data and uncertainties regarding the size and success of future research efforts.

With regard to power generation, estimates of installed geothermal electrical capacity in the U.S. by 1985 range from a conservative 5000 megawatts, assuming only technology presently available or under development, to a potential 20,000–30,000 megawatts, based on an energetic and successful research and development program by both industry and the Federal Government. If this potential could be realized, it would represent about 3% of the total electrical generating capacity of the country projected for 1985.

In addition to generating electricity, geothermal heat will undoubtedly have increasingly important applications for direct use in such diverse fields as space and industrial process heating, agriculture, refrigeration, and the production of fresh water and certain minerals. Programs to promote these kinds of direct geothermal heating applications are being pursued all over the world.

Research and Development Programs

As indicated by the qualifications placed on the above estimates, the most important factor in rapidly bringing geothermal energy into a more useful role in the U.S. is the kind of research, development, and engineering programs in this field that will be undertaken in the near future. There are many broad areas in which new technological frontiers must be aggressively explored and progress achieved as outlined in Chapter 4. The most important of these can be summarized as follows:

1. Improving our knowledge of the location, size, and type of our geothermal resources. This demands significant advancement in drilling technology and exploration and prospecting techniques.
2. Investigating the feasibility of using explosives or hydrofracturing to artificially stimulate geothermal sources, such as hot dry rock deposits.
3. Advancing the technology of generating electricity with geothermal hot waters.
4. Expanding the direct use of geothermal waters as heat for a wide variety of applications.

Legal and Regulatory Aspects

In addition to the need for successful technological achievements, there is a strong requirement for a careful analysis of the multitide of laws and regulations that govern the exploration and use of geothermal energy resources.

Three-quarters of the known geothermal energy deposits lie below land owned by the Federal Government, which must assume a leading role in the overall program of geothermal development.

Recent legislation in this field has extended the authority of the U.S. Department of the Interior to establish more precise standards for what are called "known geothermal resources areas" (KGRA's). The Secretary of the Interior is empowered to formulate and carry out regulations pertaining to the competitive leasing of such lands. The exercise of the authority conferred by this legislation will have an important bearing on the future effective use of our geothermal resources.

In accordance with these statutes, federal lands were opened to private industry in early 1974 for the first time for geothermal exploration. It is clear that there is a vigorous movement to mobilize many different kinds of private and government efforts to exploit geothermal resources and to search for more in spite of the risks and technological problems involved.

Present federal policy places major emphasis on a strong and continuous working relationship with the private geothermal energy industry, which it is hoped will assume an increasingly active and important role and accept a greater share of the risk as the whole national research program in this field begins to pay off. The hope is that such a basic policy will facilitate a rapid transfer of research results and achieve a substantial acceleration of the development of U.S. geothermal resources. Perhaps this development activity will become a kind of "geothermal rush", like the famous "gold rush" of 1849.

To whatever extent these developments occur as predicted, they will represent significant steps toward better use of this almost limitless domestic source of energy and a resulting increased conservation of previous fossil fuels. It is therefore vital that Government and private industry continue their cooperative efforts to develop geothermal energy for the benefit of the American public.

BIBLIOGRAPHY

Geothermal Energy, Carel Otte and Paul Kruger, Stanford University Press, Stanford, California, 1973, 372 pp., $17.50.

Assessment of Geothermal Energy Resources, Panel on Geothermal Energy Resources, Federal Council for Science and Technology, 1972, 100 pp., $4.75. Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

"Geothermal Power," Joseph Barnes, ***Scientific American***, 226: 70 (January 1972).

Geothermal Energy: A National Proposal for Geothermal Resources Research, Final report of the Geothermal Resources Conference, Battelle Seattle Research Center, Seattle, Washington, September 18-20, 1972, 95 pp., $1.45. Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Geothermal Resources, L. J. P. Muffler, U. S. Geological Survey Professional Paper 820, U.S. Geological Survey, Arlington, Virginia 22202, 1973, 722 pp., $9.15.

NOTE: Several of these references contain detailed lists of further citations.

APPENDIX
BASIC UNITS RELATED TO ENERGY

Electrical

The number of amperes in an electrical circuit multiplied by the voltage equals the number of watts of power or the rate at which energy is being consumed.

More briefly:

volts x amperes = watts
1000 watts = 1 kilowatt
1000 kilowatts = 1 megawatt (one million watts)

The number of watts multiplied by the time in hours equals watt-hours or the total energy expended in that time.

More briefly:

watts x hours = watt-hours
kilowatts x hours = kilowatt-hours
megawatts x hours = megawatt-hours

Note: Watts can be visualized as similar to the speed (mph) of a moving automobile, whereas watt-hours are similar to the total distance the automobile travels in a number of hours (corresponding to the total energy consumed in the trip).

Example: A car doing a steady 40 mph will go 40 miles in 1 hour, 80 miles in 2 hours, etc. Similarly, an electrical device using energy at the rate of 40 watts will consume a total of 40 watt-hours in 1 hour, 80 watt-hours in 2 hours, and so on.

Heat

A British Thermal Unit (Btu) is the amount of heat energy that will raise the temperature of 1 pound of water 1° Fahrenheit.

A calorie is the amount of heat energy that will raise the temperature of 1 gram of water 1° Celsius (Centigrade Scale).

Temperature

On the Fahrenheit scale, water freezes at 32° F and boils at 212° F.

On the Celsius (or Centigrade) scale, water freezes at 0° C and boils at 100° C.

To convert a temperature from Fahrenheit to Celsius, subtract 32 and multiply by $\frac{5}{9}$.

Example:

$$\begin{aligned} 86^\circ\text{ F} - 32 &= 54 \\ 54 \times \tfrac{5}{9} &= 30^\circ\text{ C} \\ 86^\circ\text{ F} &= 30^\circ\text{ C} \end{aligned}$$

To convert a temperature from Celsius to Fahrenheit, multiply by $\frac{9}{5}$ and add 32.

Example:

$$\begin{aligned} 20^\circ\text{ C} \times \tfrac{9}{5} &= 36 \\ 36 + 32 &= 68^\circ\text{F} \\ 20^\circ\text{ C} &= 68^\circ\text{ F} \end{aligned}$$

Mechanical

One horsepower (hp) is arbitrarily defined as the rate of expenditure of energy required to raise a 550-pound weight 1 foot in 1 second.

Length

1 inch	= 2.54 centimeters
1 foot	= .3048 meters
1 mile	= 1.609 kilometers
1 centimeter	= .394 inches
1 meter	= 3.28 feet
1 kilometer	= .624 mile (about ⅝)

Useful Conversions

746 watts	= 1 horsepower (hp)
1 kilowatt (1000 watts)	= 1⅓ hp
1 Btu	= 252 calories
1 Btu per hour	= .2931 watts
1 watt	= 3.412 Btu per hour

☆ U.S. GOVERNMENT PRINTING OFFICE: 1975 - 640-287/19

A word about ERDA . . . .

The mission of the U. S. Energy Research & Development Administration (ERDA) is to develop all energy sources, to make the Nation basically self-sufficient in energy, and to protect public health and welfare and the environment. ERDA programs are divided into six major categories:

- CONSERVATION OF ENERGY—More efficient use of existing energy sources, development of alternate fuels and engines for automobiles to reduce dependence on petroleum, and elimination of wasteful habits of energy consumption.
- FOSSIL ENERGY—Expansion of coal production and the development of technologies for converting coal to synthetic gas and liquid fuels, improvement of oil drilling methods and of techniques for converting shale deposits to usable oil.
- SOLAR, GEOTHERMAL, AND ADVANCED ENERGY SYSTEMS—Research on solar energy t heat, cool, and eventually electrify buildings, on conversion of underground heat sources to gas and electricity, and on fusion reactors for the generation of electricity.
- ENVIRONMENT AND SAFETY—Investigation of health, safety, and environmental effects of the development of energy technologies, and research on management of wastes from energy production.
- NUCLEAR ENERGY—Expanding medical, industrial and research applications and upgrading reactor technologies for the generation of electricity, particularly using the breeder concept.
- NATIONAL SECURITY—Production and administration of nuclear materials serving both civilian and military needs.

ERDA programs are carried out by contract and cooperation with industry, university communities, and other government agencies. For more information, write to USERDA–Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

United States
Energy Research and Development Administration
Office of Public Affairs
Washington, D.C. 20545